Traffic-related fine and ultrafine particle exposures of professional drivers and illness: An opportunity to better link exposure science and epidemiology to address an occupational hazard?

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HIGHLIGHTS

- Professional drivers may incur large occupational exposure to particles.
- The potential health effects of exposure are unclear.
- This article briefly reviews and updates the current state of this topic.
- Options for protecting workers and future research directions are suggested.

Keywords: air pollution, occupational exposure, particles, drivers

ABSTRACT

Exposures to traffic-related air pollution (TRAP) can be particularly high in transport microenvironments (i.e. in and around vehicles) despite the short durations typically spent there. There is a mounting body of evidence that suggests this is especially true for fine (< 2.5 μm) and ultrafine (UF, < 100 nm) particles. Professional drivers, who spend extended periods of time in transport microenvironments due to their job, may incur exposures markedly higher than already elevated non-occupational exposures. Numerous epidemiological studies have shown a raised incidence of adverse health outcomes among professional drivers, and exposure to TRAP has been suggested as one of the possible causal factors. Despite this, data describing the range and determinants of occupational exposures to fine and UF particles are largely conspicuous in their absence. Such information could strengthen attempts to define the aetiology of professional drivers' illnesses as it relates to traffic combustion-derived particles.

In this article, we suggest drivers' occupational fine and UF particle exposures is an exemplar case where opportunities exist to better link exposure science and epidemiology in addressing questions of causality. The nature of the hazard is first introduced, followed by an overview of health effects attributable to exposures typical of transport microenvironments. Basic determinants of exposure and reduction strategies are also described, and finally the state of

knowledge is briefly summarised along with an outline of the main unanswered questions in the topic area.

1. DRIVING AND TRAFFIC-RELATED AIR POLLUTION

Driving is a task central to many occupations that place a high reliance on mobility. These include police officers, taxi, bus and truck drivers, postal workers, garbage collectors and couriers, among others. While motorised vehicles (e.g. car, bus, truck, or motorcycle) are commonly the transport mode of choice for these professions, bicycles may be used by some police officers and couriers, particularly in heavily-congested cities. In Asia and the Subcontinent, traditional non-motorised transport modes that are either pedalled or pulled by a driver, such as 'cyclos' and rickshaws, remain a popular means of transport among tourists. Although each of these occupations has a unique risk profile associated with it, one hazard common to all is exposure to traffic-related air pollution (TRAP). This article focuses on this issue, with a specific focus on traffic-derived particles, and suggests options for improving the link between exposure science and epidemiology in addressing the consequences of drivers' occupational exposure.

1.1 TRAP and its significance for professional drivers

Concentrations of many air pollutants such as 1,3-butadiene, benzene, toluene, ethylbenzene, xylene, nitrogen oxides, carbon monoxide, black carbon, and both fine (< 2.5 μm, known as $PM_{2.5}$) and ultrafine (< 0.1 μm, UF) particles are elevated, albeit to different extents, on and near roadways (Batterman et al., 2002; Brugge et al., 2007; Duffy and Nelson, 1997; Hitchins et al., 2000; Peters et al., 2011). This is due to the proximity of motor vehicles from which these pollutants originate due to incomplete combustion of diesel, gasoline and other fuels. Resuspended road dust, mechanical wear of brake pads, tyres, and other vehicle components

can also contribute to increased particle levels and affect their chemical composition (Kumar et al., 2010; Riediker et al., 2004a; Schauer et al., 1996).

Individuals whose job requires that they spend long periods of time in or near vehicles (i.e. transport microenvironments) may incur substantial occupational exposures to TRAP. Numerous studies have indicated that these exposures, among other factors, may place professional drivers at greater risk of adverse health outcomes (Balarajan and McDowall, 1988; Bigert et al., 2003; Gubéran et al., 1992; Hansen et al., 1998; Rafnsson and Gannarsdóttir, 1991; van der Beek, 2011).

While several pollutants can cause negative health effects following on- or near-road exposure, fine and UF particles arguably attract most interest at present, due to the increasing weight of evidence that links them with negative respiratory, cardiovascular and neurologic effects (Peters et al., 2006). This following sections provide an overview of UF and fine particle emissions from vehicles, the health risks they pose to professional drivers, measures to protect these workers, and possible future research directions.

2. NATURE OF THE HAZARD: FINE AND ULTRAFINE PARTICLES

2.1 Sources

The overwhelming majority of UF particles in urban areas originate from vehicular fuel combustion, either as direct tailpipe emissions (i.e. primary particles) or following subsequent formation in the atmosphere (i.e. secondary particles) (Morawska et al., 2008; Kumar et al., 2010). Although diesel vehicles often make up a smaller proportion of total traffic on the road than gasoline vehicles, diesel combustion leads to greater quantities of UF and fine particles (Morawska et al., 2008).

While UF particles often constitute 80-90% of total particle number concentration (PNC, measured as particles cm^{-3}), their contribution to particle mass concentration ($\mu g\ m^{-3}$) is minimal (Cyrys et al., 2003). The reverse is the case for fine particles; that is, they make a minor contribution PNC and large contribution to particle mass, and UFP and fine particles are often only moderately correlated at best (Morawska et al., 2008). Vehicle emissions are also a significant source of fine particles, although not to the same extent as for UF particles (Schauer et al., 1996; Yue et al., 2008).

2.2 Health effects

Many epidemiologic studies performed across the world have shown an association between fine particles and respiratory and cardiovascular morbidity and mortality (Peters et al., 2011). Toxicologic, controlled and real-world exposure studies have sought to identify the mechanism(s) responsible, of which several are plausible (Nel, 2005). Compared to fine particles, less is known about UF particles. However, there is an ever-increasing volume of work that implicates them in a range of undesirable health effects (Peters et al., 2011). Their large number concentration and cumulative surface area, coupled with their small size, enables UF particles to carry pro-oxidative organic material and transition metals to the alveoli and deposit with relatively high efficiency (Delfino et al., 2005). They also have the potential to translocate to other organs, including the brain via the central nervous system (Peters et al., 2006, 2011). Due to these characteristics, UF particles may be the most damaging component of TRAP (Nel, 2005), although their toxicity relative to larger particles and the processes underpinning this remain to be fully elucidated.

2.3 Exposures in transport microenvironments

Only 1.5 h of daily commuting in passenger cars on Los Angeles roads has been estimated to constitute between 10 and 50% of total daily UF particle exposure (Fruin et al., 2008; Zhu et al., 2007). It follows that longer occupational exposures (up to 8 h or more) could make up a markedly greater proportion of total daily exposure. However, little is known about the size of this contribution.

There is evidence to suggest that time spent in transport microenvironments may increase the risk of myocardial infarction in some people, although the pollutant(s) responsible and role of confounding factors (e.g. stress) are difficult to differentiate (Peters et al., 2004). Nonetheless, fine and UF particles encountered there can be characterised by chaotic variability and concentrations 1 to 2 orders of magnitude greater than the urban ambient levels on which most epidemiologic studies are based; very short term excursions can be greater still (Knibbs et al., 2010; Apte et al., 2011). The range of UF particle exposure concentrations in transport microenvironments are described by Knibbs et al. (2011), and can vary markedly depending on a variety of determinant factors.

The short and long term effects of repeated exposures of this type, such as those incurred by professional drivers, are poorly understood. However, some recent studies have begun to illuminate the range of short-term health effects due to exposures in transport microenvironments. These are discussed below.

3. HEALTH EFFECTS OF SHORT-TERM EXPOSURES

3.1 Respiratory

Of all biological effects attributed to air pollution, those occurring in the respiratory system are probably the most extensively described. Despite this, there have been few studies to

assess respiratory effects within the context of transport microenvironments. Recent work has reported that short-term exposure to fine and UF particles of up to 2 h in transport microenvironments has been linked to small decreases in lung function and airway pH, and increases in biomarkers of inflammation (Larsson et al., 2007; McCreanor et al., 2007; Jacobs et al., 2010; Larsson et al., 2010; Strak et al., 2010; Weichenthal et al., 2011; Zuurbier et al., 2011). UF particles were better associated with these than fine particles, but in both cases there was often no evidence of a statistically significant effect.

There is some evidence to suggest asthmatic persons may be particularly susceptible to exposure in transport microenvironments, and that the severity of their disease may affect their response (McCreanor et al., 2007; Larsson et al., 2010).

3.2 Cardiovascular

An early hypothesis stated that the mechanisms of particle injury might relate to the ability of UF particles to effectively promote inflammation and increase blood clotting, and that this could play a role in cardiovascular mortality (Seaton et al., 1995). While it is now increasingly apparent that UF and fine particles are associated with adverse cardiovascular outcomes, the causative mechanisms are still being revealed, but are likely to include atherogenesis, vascular dysfunction, thrombosis and arrhythmia (Cassee et al., 2011). The cardiovascular significance of particle exposures in transport microenvironments has only recently begun to be explored.

Exposure to particles for up to 2 h has been associated with decreased heart rate variability (HRV), higher incidence of ectopic beats, and elevated biomarkers of inflammation (Adar et al., 2007; Hinds, 2010; Langrish et al., 2009, 2012; Laumbach et al., 2010; Riediker et al.,

2004a,b; Weichenthal et al., 2011; Wu et al., 2010, 2011; Zuurbier et al.., 2011b). Similar to respiratory effects, studies that measured both fine and UF particles generally found a stronger association between cardiovascular effects and the latter, though not all studies found statistically significant relationships (Zuurbier et al., 2011b). One study reported a positive association between HRV in young, healthy police officers during 9 h shifts and in-vehicle fine particle concentrations, which were generated by vehicle emissions and brake wear (Riediker et al., 2004a,b). That finding, which is in contrast to some studies performed since, was attributed to the young nature of the study group and their unusually high level of fitness compared to subjects in other studies. Another study found that brief, controlled exposures to dilute diesel exhaust during rest and exercise did not alter heart rate rhythm or variability in both healthy subjects and those with a history of cardiovascular disease (Mills et al., 2011).

The disparity between results obtained by these different studies may relate to the chemical composition of particles, among other factors (Wu et al., 2011). Until the determinants and relevance of cardiovascular effects due to particles are more completely understood, their significance to occupational exposures is challenging to summarise. The importance of future research aimed at addressing such issues is discussed in section 5.

3.3 Neurologic

UF particles are small enough to reach the brain, where they can cause oxidative stress, and exposure to particles may have deleterious neurologic effects (Peters et al., 2006). One hour of exposure to diesel exhaust has been shown to result in functional changes in the brain; albeit difficult to attribute to a single pollutant or particle size range (Crüts et al., 2008). A role for such processes in the causation and progression of neurodegenerative disease is

plausible, although there is a scarcity of data and long-term studies from which to draw firmer conclusions (Peters et al., 2006). Even less is known about acute neurologic effects following exposures in transport microenvironments.

A recent study reported that levels of serum brain-derived neurotrophic factor (BDNF) did not increase following 20 minutes of cycling near a major road, while the same exercise performed in a particle-free filtered indoor environment led to a 14% increase in BDNF (Bos et al., 2011). BDNF is important in cognition, long-term memory, and the maintenance and development of neurons. While the factors underpinning this preliminary finding are unclear, it may indicate that exposure to TRAP in transport microenvironments reduces the beneficial effects of exercise on BDNF levels to an extent. The consequences for people engaged in more sedate occupations (i.e. most professional drivers) are not clear, and further investigation of acute neurologic effects is required.

3.4 DNA damage

UF and fine particles can cause oxidative DNA damage in humans, and this is a mechanism of carcinogenesis and mutagenesis (Vinzents et al., 2005). Other air pollutants, such as benzene, are also implicated. Although the longer term consequences of pollutant mediated oxidative DNA damage in professional drivers are not well documented, the elevated incidence of several types of cancer in this group has been ascribed to TRAP exposure (Balarajan and McDowall, 1988; Gubéran et al., 1992; Hansen et al., 1998; Rafnsson and Gannarsdóttir, 1991; van der Beek, 2011). Moreover, it is timely to note that the International Agency for Research on Cancer (IARC) has recently classified diesel exhaust as carcinogenic to humans, and gasoline exhaust as possibly carcinogenic to humans (Benbrahim-Tallaa et

al., 2012). Frequent and prolonged occupational exposures to vehicle emissions are therefore very much undesirable.

A dose-response relationship has been demonstrated between UF particles in transport microenvironments and oxidative DNA damage in cyclists (Vinzents et al., 2005). A study of taxi drivers in Benin found they had elevated UF particle and benzene exposure compared to other groups, and that this was associated with greater levels of oxidative DNA damage (Avogbe et al., 2005). Physical activity, such as that required by rickshaw pullers or cyclists, can cause oxidative stress in its own right, and if combined with air pollution exposure can lead to DNA damage in excess of that due to activity alone (Pandey et al., 2006; Vinzents et al., 2005).

4. REDUCING EXPOSURE

Ventilation and filtration are two key methods to control the ingress of UF and fine particles into vehicle cabins. Minimising the amount of on-road air ventilating the cabin can be achieved by ensuring that air is recirculated rather than drawn from outdoors, and windows are closed. This is desirable when on-road concentrations exceed those in the cabin, as is often the case in the absence of significant in-cabin sources such as cigarette smoking. Although the air-tightness of vehicles can be highly variable, recirculation has been shown to be an effective method of reducing UF particle concentrations in passenger cars (Knibbs et al., 2010; Hudda et al., 2011). However, care should be taken to avoid excessive CO_2 or heat accumulation.

Properly installed and maintained high efficiency particulate air (HEPA) filters can remove effectively all on-road particles from air entering vehicle cabins, and the positive

cardiovascular effects of this approach have been demonstrated (Hinds et al., 2010). However, even basic filters offer some protection, and installing a filter capable of cleaning both outdoor and recirculated air can lower in-cabin particle levels, especially when used in conjunction with a recirculation ventilation setting (Pui et al., 2008).

Wearing a highly efficient respirator (face mask) greatly reduces exposure and has beneficial cardiovascular effects in healthy individuals and those with Coronary Heart Disease (Langrish et al., 2009, 2012). Masks can be used by drivers, cyclists and motorcyclists. It should be stressed that makeshift handkerchief masks offer little protection compared to purpose-designed respirators (Langrish et al., 2009), and the latter should be used wherever possible.

Switching from high to low traffic routes wherever possible and avoiding pollution 'hot-spots' can decrease exposures, although this is likely to be more practical for bicycle-based occupations than those in vehicles (Strak et al., 2010). This strategy, which is based on minimising exposure by increasing the distance between pollutant sources and individuals, has been shown to have positive respiratory effects in healthy and asthmatic persons (McCreanor et al., 2007; Strak et al., 2010).

Ultimately, only widespread uptake of cleaner fuels, use of exhaust treatment devices (Lucking et al., 2011), and most importantly, a reduction in the reliance on vehicular fossil fuel combustion will decrease emissions of TRAP. In the meantime, implementing measures to reduce an individual's occupational and other exposures to fine and UF particles is an appropriate preventive approach.

5. UNANSWERED QUESTIONS AND FUTURE DIRECTIONS

The sum of evidence presented in this article suggests UF and fine particle exposures in transport microenvironments elicit undesirable respiratory, cardiovascular and neurologic effects, and cause oxidative DNA damage. However, there are some limitations that require consideration when evaluating its relevance to occupational exposures. The major limitation of the studies described, well executed as they were, relates to their short duration; all but one examined exposures of 2 h or less. The translation of their findings to an occupational context without proper acknowledgement of this might therefore be perilous. Moreover, several studies were based on active transport modes (bicycles) where respiratory ventilation, and thus inhaled dose for a given exposure concentration, is markedly higher than inside vehicles (Zuurbier et al., 2009; Int-Panis et al., 2010). Nonetheless, if adverse effects are observed following brief, 'one-off' exposures to relatively modest concentrations of UF and fine particles, then much longer and repeated occupational exposures could contribute greatly to total daily exposure and lead to health effects of greater severity. Whether this is what is underpins the increased levels of morbidity and mortality observed in professional drivers is unknown at present, and further research is required to answer this question.

There is a strong and justifiable need for well-targeted studies that examine the nature of short-term exposures, their role in long-term (i.e. career-long) exposures, and linking these to outcomes observed in epidemiologic studies to better define their aetiology. This is an ideal opportunity for a cohesive and complementary integration of exposure science and epidemiology. Proper answers to the questions of 'how much?', 'where?', 'why?' from the former will benefit health effect estimates from the latter by reducing exposure misclassification. This may also shed light onto previously obscured effects.

Within this larger framework, there are numerous sub-questions that may reveal the key determinants of adverse health effects. For example, the specific chemical composition of UF and fine particles encountered in transport microenvironments and its relationship with health effects is poorly understood. Proximity to the tailpipe can result in low dilution of emissions, and oxidative potential is negatively correlated with dilution (Biswas et al., 2009). Understanding the links between exposure, internal and biologically effective doses, and how these may depend on the chemical composition of particles will assist our understanding of the mechanisms underlying particle toxicity.

Finally, as we have previously suggested with reference to the wider (i.e. non-occupational) population, exposures and health effects in developing regions have been largely overlooked (Knibbs et al., 2011). Particle concentrations in transport microenvironments can be an order of magnitude higher than in developed settings and the dominant modes of transport offer little or no protection (Apte et al., 2011; Jinsart et al., 2012; Knibbs et al., 2011). The sheer number of people coming into contact with transport microenvironments in developing cities means that the greatest exposure burdens, and thus greatest potential benefits following intervention or mitigation, are likely to exist in these areas. With transport microenvironments contributing overwhelmingly to particle exposures of professional drivers, addressing this and the other shortcomings described above should be a priority.

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